UTILITY ADVANCED TURBINE SYSTEMS PROGRAM (ATS)

TECHNICAL READINESS TESTING AND

PRE-COMMERCIAL DEMONSTRATION

CONTRACT NO. DE-FC21-95MC32267

FINAL

QUARTERLY TECHNICAL PROGRESS REPORT TPR-18
For the Period July 1, 2000 to September 30, 2000

to the

U.S. DEPARTMENT OF ENERGY

Office of Fossil Energy

National Energy Technology Laboratory

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Submitted by

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ABSTRACT

The objective of the ATS program is to develop ultra-high efficiency, environmentally superior and cost competitive gas turbine systems for base load application in utility, independent power producer and industrial markets. Specific performance targets have been set using natural gas as the primary fuel:

- System efficiency that will exceed 60%(lower heating value basis) on natural gas for large scale utility turbine systems; for industrial applications, systems that will result in a 15% improvement in heat rate compared to currently available gas turbine systems.
- An environmentally superior system that will not require the use of post combustion emissions controls under full load operating conditions.
- Busbar energy costs that are 10% less than current state-of-the-art turbine systems, while meeting the same environmental requirements.
- Fuel-flexible designs that will operate on natural gas but are capable of being adapted to operate on coal-derived or biomass fuels.
- Reliability-Availability-Maintainability (RAM) that is equivalent to the current turbine systems.
- Water consumption minimized to levels consistent with cost and efficiency goals.
- Commercial systems that will enter the market in the year 2000.

In Phase I of the ATS program, Siemens Westinghouse found that efficiency significantly increases when the traditional combined-cycle power plant is reconfigured with closed-loop steam cooling of the hot gas path. Phase II activities involved the development of a 318MW natural gas fired turbine conceptual design with the flexibility to burn coal-derived and biomass fuels. Phases I and II of the ATS program have been completed. Phase III, the current phase, completes the research and development activities and develops hardware specifications from the Phase II conceptual design.

This report summarizes Phase III extension activities for a three month period. Additional details may be found in monthly technical progress reports covering the period stated on the cover of this report. Background information regarding the work to be completed in Phase III may be found in the revised proposal submitted in response to A Request for Extension of DE-FC21-95MC32267, dated May 29, 1998 and the Continuing Applications of DE-FC21-95MC32267, dated March 31, 1999 and November 19, 1999.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The objective of the ATS program is to develop ultra-high efficiency, environmentally superior and cost competitive gas turbine systems for base load application in utility, independent power producer and industrial markets. In Phase I of the ATS program, Siemens Westinghouse found that efficiency significantly increases when the traditional combined-cycle power plants is reconfigured with closed-loop steam cooling of the hot gas path. Phase II activities involved the development of a 318MW natural gas fired turbine conceptual design with the flexibility to burn coal-derived and biomass fuels. Phases I and II of the ATS program have been completed. Phase III, the current phase, completes the research and development activities and develops hardware specifications from the Phase II conceptual design. This report summarizes Phase III activities for the three month period July 1, 2000 to September 30, 2000.

Phase 3 extension originally involved no load testing of the ATS turbine generator. A redefinition of Phase 3 extension tasks was submitted as a continuing application to the Department of Energy on March 31, 1999. The continuing application continues to focus on critical engineering, manufacturing, development and testing to verify the readiness of ATS technology for commercial application. Approval of the continuing application was received in June 1999. A second continuation application was submitted in November 1999.

Installation of all of the piping systems to support running of the new rig is nearly complete to the point of connecting to the existing combustion test rig piping. An RFQ was generated and sent out to 4 different vendors for the design and fabrication of the vane cascade holder, sidewalls and side exhaust duct.

Test data analysis is continuing with for the row 1 blade using Tascflow. Tascflow representatives will visit SWPC Orlando to provide support in this effort.

The testing for catalyst durability and performance has been initiated. A few problems at the onset of the test caused minor delays. The problems were corrected and the testing restarted.

Techniweave performed testing and finalized the results on rope sealing which indicates that a groove width equal to the rope seal diameter yields the best results. Testing is continuing with a final report to be issued in October.

Successful casting trials for single-crystal inner shrouds in CMSX-4 were held. The inner shrouds are being evaluated for subsequent processing and will be used further to support the programs machining development operations.

Test samples continue to accumulate high temperature and pressure exposure in the ORNL steam test rig. A major milestone was accomplished in September with the full scale internal aluminizing of the ATS transition steam passages. Additional analysis is ongoing.

The mechanical testing of the experimental vane alloy is complete along with the weld testing. The mechanical results indicate the tensile properties of the alloys meet the requirements of PDS

15119Z4. The weld testing has confirmed the optimum zirconium and boron content for maximizing the weldability of IN-939.

Testing continues on the APS coatings at Waltz Mills. EB-PVD coated specimens were cycled at the Waltz-Mill high heat flux test facilities under ATS temperature conditions to determine the limitations under cyclic loading.

The final 1800-second hold time LCF testing of IN939 is now complete. The first of the LCF tests to evaluate the effect of coatings on IN939 creep-fatigue properties has been started. Testing to understand strain ratio and coating effects is progressing to plan.

BFH coating on a flat plate qualification was completed successfully. The next step will be to qualify a combustor basket coating application. LCF testing of BFH coating on Hastelloy-X is nearly complete. Tests are planned at NASA to define the BFH coating maximum surface temperature capability.

The row 1 vane alternative design is progressing well. Tooling is complete for the necessary wax dies. Wax casts have been wax welded together and x-rayed to determine the condition of inner cores. A total of 4 vanes have been cast which will be used by the machining vendors to validate their processes.

A thermal paint test was conducted in early July at the Lakeland site. Results are pending final evaluations. Heated fuel tuning was started and commissioned. The engine has completed its contract performance test and overspeed trip verification test. Commercial acceptance by the customer was accomplished in August.

The final Empire test review was held. Resultant action items require further data reduction and analysis. Completion of action items shall conclude the Empire test program.

Mixing tests of the ATCC3 full size modules is continuing. The third module makes further improvements from the first two and is in mechanical analysis for a modified pre-mixer design. The initial design warped during testing causing improper mixing. Several changes will me made to eliminate the high thermal stresses.

INTRODUCTION

BACKGROUND

The National Energy Strategy (NES) calls for a balanced program of greater energy efficiency, use of alternative fuels, and the environmentally responsible development of all U.S. energy resources. Consistent with the NES, an U.S. Department of Energy (DOE) program has been created to develop Advanced Turbine Systems (ATS). The Siemens Westinghouse ATS Program is funded and directed by DOE's National Energy Technology Laboratory (FETC). The technical ATS requirements are based upon two workshops held in Greenville, SC that were sponsored by DOE and hosted by Clemson University. The objective of this 8-year program, managed jointly by DOE's Office of Fossil Energy, and, Office of Conservation and Renewable Energy, is to develop natural-gas-fired base load power plants that will have cycle efficiencies greater than 60%, lower heating value (LHV), be environmentally superior to current technology, and also be cost competitive. The program will include work to transfer advanced technology to the coal- and biomass-fueled systems being developed in other DOE programs.

METHODOLOGY

The Advanced Turbine Systems program is structured into four elements:

- Innovative Cycle Studies
- Utility Advanced Turbine Systems
- Industrial Advanced Turbine Systems
- Technology Base

Within each program element there are several planned phases. For example, the Innovative Cycle Studies element includes two phases.

- Program Definition/Planning Studies
- Concept Development

The objective of the ATS Program is to develop ultra-high efficiency, environmentally superior, and cost-competitive gas turbine systems for base-load application in utility, independent power producer, and industrial markets. Specific performance targets have been set using natural gas as the primary fuel:

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- An environmentally superior system that will not require use of post-combustion emissions controls under full-load operating conditions.
- Busbar energy costs that are 10% less than current state-of-the-art turbine systems, while meeting the same environmental requirements.
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In Phase I of the ATS program, Siemens Westinghouse found that efficiency significantly increases when the traditional combined-cycle power plants is reconfigured with closed-loop steam cooling of the hot gas path. Phase II activities involved the development of a 318MW natural gas fired turbine conceptual design with the flexibility to burn coal-derived and biomass fuels. Phases I and II of the ATS program have been completed. Phase III, the current phase, completes the research and development activities and develops hardware specifications from the Phase II conceptual design. Phase 3 extension activities focus on critical engineering, manufacturing development, and testing to verify the readiness of ATS technology for commercial applications.

This report summarizes Phase III extension activities for a three month period. Additional details may be found in monthly technical progress reports covering the period stated on the cover of this report. Background information regarding the work to be completed in Phase III may be found in the revised proposal submitted in response to A Request for Extension of DE-FC21-95MC32267, dated May 29, 1998 and the Continuing Applications of DE-FC21-95MC32267, dated March 31, 1999 and November 19, 1999.

RESULTS AND DISCUSSION

11.0 PROGRAM MANAGEMENT

A quarterly review was held in August in Orlando, Florida. The review covered the current status of the various tasks in the ATS program as well as a review of the progress at the Lakeland site.

12.0 DEVELOPMENT ENGINEERING

12.1 VERIFICATION TESTS

Vane Cascade Inlet piping system fabrication is complete and installation is nearing completion. All other piping systems have been completed and installed to the point where they will be tied in to existing combustion test rig piping. A work specification was prepared for design and fabrication of the vane cascade holder, side-walls and side exhaust duct and sent out to four different vendors for quotations. The hot fuel gas valving and measurement instrumentation was removed from its current location and will be installed on the overhead platform near the new rig.

Turbine Test Data Analysis Continuing with row 1 blade analysis utilizing Tascflow. Tascflow representatives will visit SWPC Orlando to provide additional analysis support.

Turbine Root Blade Verification Hamilton has located a test disc for use in the new test. SWPC Orlando is working with the Hamilton plant to determine the costs associated with this disc and providing the necessary machining requirements needed to complete the disc.

Turbulator Model Tests No scheduled progress to report.

12.2 C. T. ENGINE DEVELOPMENT ENGINEERING

Combustion System Development The 500-hour durability and catalyst performance test was started at STC. The test was shutdown prematurely due to a calibration problem between the thermocouple and the gas-chromatograph as well as excessive metal temperatures on the pressure vessel due to minor fitting leaks and cracks in the ceramic liner. The problems have been corrected and the testing has been restarted.

Advanced Seal Development Techniweave performed testing and finalized the results on rope sealing which indicates that a groove width equal to the rope seal diameter yields the best results. Additional testing to alter the groove width and depth indicates that a shallower groove is required for the compression load of the W501FD R2 seal holder than was initially tested. Based on these results a rope seal design will be produced with a peer design review held in October. Technetics completed testing of transition mouth brush seals determining that PM2000 is not a viable option for brush seals and that the ceramic brush seals are. Additional testing is continuing through early October on brush seal technologies with a final report to be issued in October.

Thin Wall Casting Development Two successful casting trials were held for single crystal inner shrouds in CMSX-4. The inner shrouds are being evaluated for subsequent processing. STC has been working with TurnTech for EDM machining operations on the inner shrouds. The shrouds will be EDM wire sliced to allow for machining of the cooling features. PCC has completed the tooling and has initial wax poured for the airfoils. These components will need to be x-rayed prior to wax weld to verify the airfoil cores are intact.

12.3 MATERIALS DEVELOPMENTAL ENGINEERING

Steam Effects on Materials Test samples continued to accumulate high temperature, high-pressure exposure in the ORNL steam test rig with the next scheduled examination planned for August 2000. A Major milestone was accomplished in September with the full scale internal aluminizing of the ATS transition steam passages. The gas phase process uniformly applies aluminum to the interior surface, which reacts with the alloy to form a protective nickel aluminide. Additional analysis is ongoing with the completion of the coating qualification documentation anticipated for October – November timeframe.

Advanced Vane Alloy The mechanical testing of the experimental vane alloy is now complete. The results indicate that the tensile properties of the experimental alloys meet the requirements of PDS 15119Z4. The weld testing has been completed and this data has confirmed the optimum zirconium and boron content for maximizing the weldability of IN-939. ORNL is continuing the analysis of these weld specimens and should be complete by November.

TBC Life Prediction Testing continued on the APS coatings at Waltz Mills at 2100 and 2200ºF. Working with Oak Ridge National Labs on the kinetics of sintering on bond coat adhesion. Effort to determine the sintering behavior of 8YSZ coatings is ongoing within a user program at ORNL. EB-PVD coated

specimens were cycled at the Waltz-Mill high heat flux test facilities under ATS temperature conditions to determine the limitations under cyclic loading. Both the TGO thickness and hold time at high temperature were varied. The results show a cyclic dependency of failure time, where the total hot time to failure decreases rapidly with decreasing hold time per cycle. Finite element calculations were performed and are currently ongoing to further understand and describe the cyclic failure mode.

ATS NDE No scheduled activities this quarter.

TMF testing row 1 blade alloy The final 1800 second hold time LCF testing of IN939 at temperatures of 800, 850, and 950ºC and a strain ratio of R = -infinity is now complete. The first of the LCF tests to evaluate the effect of coatings on IN939 creep-fatigue properties has been started. The testing to understand strain ratio and coating effects is progressing to plan and testing with zero hold time/0.5% strain range at temperatures of 800 and 900ºC has been completed. Additional testing will concentrate on generating strain ratio and coating data with a hold time of 300 seconds.

Ring Segment Abradable Coating Development Vendor qualification is in progress at Stolper. BFH coating on a flat plate qualification was completed successfully. The next step is to qualify a combustor basket coating application. Two baskets will be used. A report will be issued upon completion. LCF testing of BFH coating on Hastelloy-X is nearing completion. Preliminary results indicate the coating has no effect on substrate LCF life. Evaluation of APS dense alumina overlayer on machined BFH has shown that the coating is durable over a range of test conditions, which included thermal shock, thermal cycling and isothermal exposure. There was no coating spallation or debond. Tests are planned at NASA to define the BFH coating maximum surface temperature capability.

Alternate Alloy Development The LCF tests as well as the HCF tests for phase 1 testing of PWA 1483 in standard heat treatment condition on uncoated specimens have been finished. Resulting data will be placed into the database for further evaluation. HCF/LCF tests on aluminide coated specimens are still in progress.

Liquid Metal Cooling Casting No scheduled activity this quarter.

12.4 C. T. MANUFACTURING ENGINEERING

Row 1 Blade and Vane Alternative Design Tooling is complete for all castings. Casting trials for the inner shrouds have resulted in enough test pieces to supply the machining vendor with parts for wire slicing. Wax casts for the Hot Cascade

Vane have been wax welded together and x-rayed to determine condition of inner cores. A total of 4 vanes have been cast which will be used by the machining vendors to validate their processes. Additional support within the tooling for wax molding will be required to mitigate TE core breakage believed to be caused during hot wax injection. Additional trials are in progress with cast parts being ready by early December. These trials should validate previous lessons learned from the original casting trials.

12.5 GENERATOR DEVELOPMENTAL ENGINEERING

ATS Class G Stator Development. No scheduled activity.

12.6 ADAPTATION TO COAL AND BIOMASS FUELS

No scheduled activity.

13.0 C. T. MANUFACTURING DEVELOPMENT AND TOOLING

13.1 DELETED

13.2 MANUFACTURING & TOOLING DEVELOPMENT ENGINEERING

No scheduled activity.

13.3 DELETED

13.4 MANUFACTURING VERIFICATION TESTS

No scheduled activity.

14.0 ATS TECHNOLOGY VERIFICATION PROGRAM

14.1 STEAM COOLED COMPONENT & AERO-THERMAL DESIGN VALIDATION TEST

A thermal paint test was conducted in early July and initial indications are still under evaluation. Heated fuel tuning was started and commissioned. Attempts at firing on oil have also begun but have had limited success to date. The engine experienced a trip from full power during the performance test due to a failure of a transition steam cooling pipe weld. Inspection revealed no other transition problems. The Lakeland engine completed its contract performance test and overspeed trip verification test. Commercial acceptance by the customer was accomplished in August.

14.2 ADVANCED VISCOUS COMPRESSOR TEST

The final Empire test review was held. Resultant action items require further data reduction and analysis. Completion of action items shall conclude the Empire test program.

14.3 CATALYTIC COMBUSTOR TEST

Mixing tests of the second ATCC3 full size module have been completed at PCI. The mixing is significantly better than in module #1, but there is still room for improvement. The second ATCC3 full size module was subsequently tested which showed much more uniform catalyst temperatures than with module #1. Both NOx and CO emissions were better than previous, but the NOx target has still not been achieved. Module number 3 makes further improvements than the first two and is in mechanical analysis for a modified pre-mixer design. The initial design warped during testing causing improper mixing. Several changes will be made to eliminate the high thermal stresses.

14.4 STEAM COOLED VANE TEST

No scheduled activity.